

## FLUENT CONTROL VALVE

This utility patent application claims priority under 35 U.S.C. 119(e) from application 60/413,208, filed on September 24, 2002, the subject matter of which is herein incorporated by reference.

### BACKGROUND INFORMATION

### FIELD OF THE INVENTION

**[001]** The invention relates to the field of fluid control valves. More particularly, the invention relates to fluid control valves for regulating supersonic gas flow.

### DESCRIPTION OF THE PRIOR ART

**[002]** The purpose of a supersonic flow valve, for example, a thruster valve in a rocket booster or divert thruster, is to align the momentum of fluid flow with the direction of the desired thrust. During optimal performance, all the velocity components of the fluid flow are aligned with the direction of flight or thrust. Vectored flow, that is, flow that has velocity components at an angle relative to the direction of flight, will produce a vectored thrust. Also, if the flow is not properly aligned and turbulence or flow separation occurs, the separation will dissipate kinetic energy in the flow, thus reducing the velocity and the amount of thrust obtained from the fuel.

**[003]** Conventional valves used to control supersonic fluid flow typically have a cone-shaped pintle, typically a 45-degree cone, that seats in the orifice of the nozzle. When the valve closes, the pintle stops flow through the orifice; when it opens, the pintle not only allows fluid to flow into the nozzle, but also provides a boundary surface that serves to align the velocity components of the fluid flow. Depending on the particular

application, the boundary surface is shaped to guide the flow toward the nozzle exit, with the least amount of losses due to friction and/or flow separation.

**[004]** Several disadvantages are inherent with the use of a 45-degree pintle in applications of supersonic fluid flow. First and foremost is the problem of material ablation in such pintles as a result of rapid heat transfer from the fluid to the tip of the pintle. **FIGS. 1A – 3C** listed below are illustrations of the typical construction and flow conditions within a conventional 45-degree pintle valve. **FIG. 1A** is a perspective view and **FIG. 1B** a cross-sectional view of the convention 45-degree valve, showing the pintle and the nozzle. **FIGS. 2A – 3C** are color graphs of computational fluid dynamics analyses of fluid flow, whereby it is noted that the pintle is shown facing upward instead of downward as in **FIGS. 1A, 1B**, and that fluid flow through the nozzle is toward the upper end of the graph. **FIG. 2A** illustrates temperature (T) conditions, **FIG. 2B** illustrates pressure (P) conditions, and **FIG. 2C** illustrates Mach (M) conditions in the valve during fluid flow.

**[005]** Color and color gradations are indicators of a change in the respective P, T, and M conditions, with red representing a maximum condition, and dark blue a minimum condition. A shock wave is indicated by the color yellow. In **FIGS. 2A and 2B**, the 45-degree pintle valve is shown fully open, providing a throat in the area between the pintle and the inlet to the nozzle. A shock wave arises as a result of the rapid expansion of the fluid as it flows into the nozzle. **FIGS. 2A and 2B** show two areas of high pressure and high temperature, respectively. The first area of high temperature/high pressure is located in the plenum of the valve and ends at the edge of the nozzle inlet. This first area contributes largely to the high heat flux in the nozzle and leads to a high rate of material ablation and erosion at the nozzle inlet. The second area is situated directly at the tip of the pintle. This area is particularly problematic due to the high surface to volume ratio of material at the tip of the pintle to the amount of heat being transferred from the fluid to the pintle. Because of this, the material at the tip rapidly melts away, thereby drastically changing the geometry of the flow control surface. Any change in

geometry results in a rapid deterioration of thruster performance. In some conventional valves, the tip of the pintle and the nozzle inlet are coated with rhenium, a metal capable of withstanding the high temperatures generated in such a valve. Although rhenium can minimize the material ablation in the valve, it has disadvantages in that it is an extremely heavy material and also very expensive and difficult to obtain.

**[006]** Accurate alignment of the 45-degree pintle and nozzle orifice is a critical aspect of good performance of the conventional 45-degree pintle valve in supersonic flow control applications. Any misalignment of the pintle leads to significant performance degradation. For example, if the pintle is off-center, flow will be greater on one side of the orifice, resulting in a higher pressure on that side. The gas under the higher pressure will tend to flow into areas of lower pressure, causing secondary flow fields with their inherent energy losses due to additional heating and separation. Furthermore, vibrational excitations emanating from the structure/vehicle may also cause a misalignment of the pintle, which, if the pintle and nozzle touch, may result in catastrophic failure of the valve.

**[007]** The fact that the 45-degree pintle is a rigid mass situated in the flow path is a further disadvantage. The fluid flow is forced along the boundary surface of the pintle as it passes through the throat, resulting in loss of kinetic energy in the flow due to friction against the boundary surface. Also, gaseous fluids are often contaminated with solid particles. These solid particles, being heavier than the gas particles, collide with the pintle and nozzle, abrading and eroding the boundary surface and exacerbating the material ablation resulting from heat transfer.

**[008]** There are many applications for booster or thruster valves in which it is critically important that the fluid flow be precisely controlled. One example is the use of fluid flow valves in missile defense systems in which a seeker component of a missile system locks onto the flight path of an in-coming hostile missile, with the purpose of intercepting the flight path and destroying the missile. Currently, the valve technology in such guidance and seeker systems uses the traditional pintle design and nozzle.

Typically, these valves operate in the full-on and full-off positions, and consequently, are pulsed as a means of precisely controlling the mass flow of the hot gases and, thus, the thrust. In some applications, these cone pintles are easily operable in an on-off mode because the stroke length (actuation length) is so long. Due to the severe weight and space constraints that are typically applied to the construction of vehicles in a missile system, operating a thruster valve in pulse-mode has disadvantages that affect accuracy and cost of the missile system. For example, the pulsing produces significant structural vibrations that severely hamper the operation and performance of the high-precision components in the guidance and seeker systems on the vehicle. Consequently, the seeker housing has to be vibrationally isolated from the body of the vehicle in order to maintain proper performance, and this is technically a difficult and costly task.

**[009]** Another type of known valve includes a pintle that is very slightly angled, about  $2^{\circ}25'$ , rather than having the 45-degree type pintle discussed above. **U.S. Patent 3,975,116 (Feild; issued 1976)** teaches such a valve for hydraulic operations. A severe disadvantage of the **Feild** device for supersonic flow applications is that it teaches a straight-edge nozzle inlet (orifice), that is, a  $90^{\circ}$  drop-off at the edge of the orifice. The rate of expansion is uncontrolled with such a sudden drop-off, making the device unsuitable for use with supersonic fluid flow.

**[0010]** What is needed, therefore, is a fluid control valve that provides enhanced valve performance and a longer operational life. What is further needed is such a valve that reduces heat transfer loads in the nozzle throat region, reduces kinetic energy losses, and optimizes the flow path. What is yet further needed is such a control valve that minimizes response time and reduces the power required to actuate the valve. What is still yet further needed is such a device that reduces vibrational stress on surrounding system components.

## BRIEF SUMMARY OF THE INVENTION

**[0011]** For the above cited reasons, it is an object of the present invention to provide a continuously variable valve that is suitable for controlling supersonic fluid flow, and that provides enhanced performance and a longer operational life. It is a further object of the invention to provide such a valve that reduces heat transfer loads in the nozzle throat region, reduces kinetic energy losses, and optimizes the flow path. It is a yet further object to provide such a control valve that minimizes response time, minimizes kinetic energy losses, and enables precise control of fluid flow through the valve without imparting vibrational stress to surrounding system components.

**[0012]** The objects are achieved by providing a variable fluent control valve (FCV) comprising two circular plates — a fluid control plate with a very slightly angled physical flow control surface (FCS) and a nozzle plate that includes a physical nozzle having a physical nozzle inlet (PNI). The fluid control plate is arranged opposite the nozzle plate in a plenum into which fluid enters at high pressure and high temperature from one or more fluid ports. Generally, the fluid is in a gasified state before it enters the plenum and hereinafter, when discussing fluid flow through the FCV, it will be understood that the fluid is primarily in a gaseous state which may contain some contamination in the form of solid particles.

The FCS on the fluid control plate is a key feature of the invention. This FCS has a very small angle relative to the horizontal plane of the major diameter of the fluid control plate, such that, at any particular position of the FCV, the distance between the fluid control and nozzle plates at the outer perimeter of the fluid control plate is greater than the distance between the two plates at the physical nozzle inlet (PNI). The fluid control plate may be translatable in an axial direction relative to a fixed nozzle plate for metering the flow through the nozzle, or both plates may be adapted to translate axially. Due to a pressure differential across the FCV, when the FCV is open, the fluid flows from the plenum into a nozzle throat area between the fluid control plate and the nozzle

plate in a plane substantially parallel to that of the surface of the nozzle plate, radially from the outer perimeter of the two plates toward the PNI.

**[0013]** A unique feature of the FCV according to the present invention is that a “hydrodynamic pintle” or “hydrodynamic control surface” forms in the center of the PNI that adapts to the expansion needs of the fluid during supersonic flow. Unlike traditional pintles that are rigid, solid components, the hydrodynamic pintle provides a flow control surface the shape of which adapts dynamically to the nozzle configuration and FCV opening. The flow area between the plates decreases as the fluid flows evenly and radially inward toward the PNI, resulting in increased fluid velocity. The fluid-fluid interaction that takes place as fluid flows from all sides toward the center of the PNI gives rise to the hydrodynamic pintle which redirects the flow direction of the fluid 90° toward the nozzle exit, *i.e.*, in a direction substantially parallel to the axial direction. This hydrodynamic control surface (HCS) changes shape in the course of valve operation, becoming longer or shorter, or disappearing as the FCV opens and closes, thereby providing a hydrodynamic wall or control surface that effectively serves to redirect the fluid flow down toward the nozzle exit. Hereinafter, the “hydrodynamic control surface” or “hydrodynamic pintle” will be referred to as the HCS, regardless of its instantaneous shape.

**[0014]** In normal operation, the FCV opens and closes in rapid succession, thereby opening and closing a nozzle throat with a flow area that is constantly changing. The flow velocity of the fluid changes as the flow area of the nozzle throat changes, and the changes in flow velocity effect changes in the flow pressure and temperature. In supersonic flow, flow velocity increases as the flow area increases. The fluid closest to the nozzle plate expands in area rapidly as it flows through the narrow nozzle throat region into the expanding PNI, resulting in a higher Mach number flow in an area of lower pressure, whereby  $\text{Mach number} = (\text{velocity of fluid flow})/(\text{local speed of sound})$ . The fluid in the plenum flows with even distribution around the perimeter of the fluid control plate toward the center of the PNI. Fluid flowing into the PNI from one direction

collides in the center with fluid flowing into the PNI from other directions, causing an area of recirculation to form, the size and shape of which is dependent upon the expansion needs of the fluid. Studies have shown that the HCS is generally a recirculation region that remains relatively stable in the center of the PNI, increasing and decreasing somewhat in dimension in the axial direction of the FCV as the FCV opens and closes. At the higher openings, the HCS may cease being a recirculation region and become merely an area of higher pressure fluid and low subsonic flow. The boundary of the HCS separates supersonic flow from subsonic flow in the PNI. In other words, the HCS effectively provides a hydrodynamic "pintle" that adapts to the momentary configuration of the FCV.

**[0015]** As the fluid flows into the PNI, it is redirected toward the nozzle exit by the flow control surface of the FCV, which includes the physical FCS of the fluid control plate and the HCS. The velocity of the fluid increases as it flows through the nozzle throat into the PNI, due to the increasing area downstream from the throat region, and continues to increase as it is redirected down toward the nozzle exit due to the greater expansion in the flow area of the nozzle. A normal shock wave forms in the throat region as a result of the increasing velocity and, as the fluid flows through this shock wave, the pressure and temperature of the fluid drop significantly and the velocity becomes supersonic. The drop in temperature and pressure reduces the heat transfer to the nozzle. The temperature of the fluid near the center of the flow is the hottest, but this fluid only comes into contact with the HCS and the FCS on the fluid control plate. The FCS, being relatively flat compared to the 45-degree cone-tip of the traditional pintle, provides a much lower surface to volume ratio to amount of heat transfer than does the 45-degree cone tip and, therefore, provides reduced heat loads over that of the traditional pintle. The fluid is in contact with a much reduced surface area of the FCV, be it with the physical FCS or the physical nozzle, and, as a result, the physical nozzle absorbs less energy from the fluid flow and the physical FCS can better withstand the heat transfer loads. The material ablation of the nozzle and, above all, of the physical FCS, is greatly reduced, thereby increasing the operational life of the FCV.

Furthermore, the reduced energy absorption improves the performance of the FCV. In addition, in solid-propellant rocket motors, the flow path helps direct solid particles toward the center of the nozzle and away from the nozzle walls. The solid particles are heavier than the fluid and, as the direction of flow changes, their momentum causes them to collide in the center of the nozzle, away from the walls, where they are redirected downward toward the nozzle exit. Thus, the HCS at the center of the PNI prevents the particles from impinging on the surfaces of the physical FCS and the physical nozzle walls, thereby minimizing or eliminating significant erosion problems encountered in traditional pintle nozzles.

**[0016]** Computational fluid dynamic analyses of fluid flow in the FCV according to the invention and in traditional pintle valves show significant differences in uniformity of flow. In traditional pintle valves, flow near the tip of the 45-degree pintle is subsonic, *i.e.*, has a low Mach number, and this subsonic flow extends far down into the center of the nozzle. By contrast, supersonic flow in the FCV according to the invention is much more uniform across the nozzle below the HCS and at the nozzle exit, the velocity components of the flow are in alignment with the direction of thrust, and pressure and temperature are significantly lower at the PNI in the throat region and along the nozzle wall. The HCS flattens out as the FCV opens, and becomes more cone-shaped as the FCV closes, and, depending on the expansion needs of the fluid as it flows into the nozzle and is re-directed 90° toward the nozzle exit, the HCS may eventually disappear. The FCV according to the invention effectively lengthens the nozzle by extending it up into the area between the two plates, while simultaneously enabling the use of a physically smaller nozzle. This provides two advantages. For one, having a longer effective control surface results in better flow alignment. For another, the use of a physically shorter, smaller nozzle, made possible by the essentially flat configuration of the fluid control plate, allows a reduction in the weight and size of the FCV. The shape of the HCS is determined by the radius of the physical FCS ( $R_2$ ), the radius of the nozzle throat ( $R_1$ ), and the radius of the PNI (curved nozzle wall entering the physical nozzle). The optimum FCV design defines a nozzle inlet radius that provides the proper



rate of fluid expansion to maintain a sufficiently low temperature in the fluid flow next to the nozzle wall for the particular application.

**[0017]** Computational fluid dynamic (CFD) analysis indicates that the FCV produces a flow with minimal to no recirculation (beyond that of the HCS) within the valve. Hence, the FCV will dramatically improve the flow control, and consequently, the maneuverability and reliability of missiles and other vehicles that require very precise attitude and heading control. This improved performance of the FCV also effects substantial savings in vehicle weight.

**[0018]** Secondary flowfields that are generated within the plenum chamber are damped before entering the inlet to the FCS. These secondary flowfields are known to increase heat transfer and ablation significantly in pintle or traditional style supersonic nozzles. The damping of these flowfields minimizes the heat transfer and ablation of the nozzle and valve materials. This characteristic of the FCV allows the utilization of lower cost and lighter weight materials than do the traditional 45-degree pintle valves.

**[0019]** In rocket thruster applications, such as kinetic kill vehicles for missile defense, the FCV according to the invention, with its "hydrodynamic pintle" or HCS, eliminates thrust variations due to vibrations in the system. In the traditional design, a vibrating or off-axis pintle effects changes in the flow path that result in changes in the thrust and exacerbates the problem of ablation and erosion of the nozzle throat and pintle. By contrast, an off-axis or vibrating FCS according to the present invention does not affect the flowpath through the nozzle. Hence, the design requirements regarding rigidity and alignment of the vehicle structure can be relaxed, thereby reducing the cost of fabricating variable thrust rocket motors.

**[0020]** The FCV according to the invention has been studied in hydraulic applications and the following characteristics have been observed. The pressure drop across the FCV is much lower than in traditional pintle valves because of the absence of recirculation and flow separation. Thus, the FCV is much quieter in operation. Flow

control is linear with opening of the FCV, down to essentially zero mass flow. Hence, the FCV provides a nearly infinite turn-down ratio and, consequently, serves as a very precise flow meter.

**[0021]** The response time of the FCV has been shown to be extremely fast in hydraulic applications. This is due to the very short stroke length required to move the FCV from full open to completely closed. Inherent in the design of a traditional pintle valve is that the pintle, to open the valve to the same degree, travels a greater distance than does a flat or nearly flat surface. That is, the stroke length of the FCV between full-open position and full-close position is shorter than the necessary stroke length in a traditional pintle valve between full-open and full-close positions. Minimizing the stroke length results in a quicker response time and also requires less power to actuate the FCV. Also contributing to the reduced power requirements to actuate the FCV is the fact that, because of the slight angle on the FCS relative to the surface of the nozzle, fluid at line pressure fills the space between the fluid control plate and nozzle plate when the FCV closes the exit nozzle entrance.

**[0022]** Further, the FCV according to the invention is extremely resistant to wear, even when the fluid is contaminated with solid particles. This further supports the findings of minimal turbulence and recirculation within the FCV. All of these observations are indications of superior performance potential for the FCV in supersonic fluid flow applications.

**[0023]** Experiments have been carried out with the FCV according to the invention under conditions of cold flow and hot flow, relevant to actual rocket thruster conditions, with regard to temperature and pressure, low pressure, subsonic and supersonic gas flow. The results show that the mass flow versus valve opening is linear with subsonic and supersonic flow throughout the FCV for constant plenum pressure conditions. Two-dimensional and three-dimensional CFD analysis has also been conducted on the FCV. In the case of supersonic flow, the FCV continues to show a linear relationship between mass flow and valve opening. A normal shock wave appears between the physical FCS

and the nozzle inlet surface, whereby the opening of the FCV controls the height of the throat area, and therefore, of the normal shock. Hence, the valve opening controls the mass flow and, therefore, the overall thrust of the system. This provides the capability of precisely controlling the mass flow or thrust through the nozzle. In addition, the flow remains uniform throughout the nozzle, unlike in traditional plug or pintle type nozzles in which supersonic flow occurs near the nozzle walls and subsonic flow extends far down into the center of the nozzle.

**[0024]** Because the normal shock occurs between the FCS and the nozzle plate, the nozzle length actually extends 90 degree up around the radiused corner of the inlet onto the surface of the nozzle plate. This allows the overall physical length of the nozzle to be shortened, making a much more compact thruster.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0025]** The application as filed contains at least one drawing executed in color. Color drawings will be provided with copies of this patent or patent application publication by the Office upon request and payment of the necessary fee.

**[0026]** **FIG. 1A** is a perspective view of a traditional flow control valve with a 45-degree cone-shaped pintle and nozzle (prior art).

**[0027]** **FIG. 1B** is a side view of the control valve of **FIG. 1A**.

**[0028]** **FIG. 2A** is a CFD color graph of the temperature regions in a traditional 45-degree pintle valve that is 80% open (prior art).

**[0029]** **FIG. 2B** is a CFD color graph of the pressure regions in a traditional 45-degree pintle valve that is 80% open (prior art).

**[0030]** **FIG. 2C** is a CFD color graph of the Mach number distribution in the fluid flow of a traditional 45° valve (prior art).

**[0031] FIG. 3A** is a CFD color graph of the temperature regions in a traditional 45-degree pintle valve that is 60% open (prior art).

**[0032] FIG. 3B** is a CFD color graph of the pressure regions in a traditional 45-degree pintle valve that is 60% open (prior art).

**[0033] FIG. 3C** is a CFD color graph of the Mach distribution in a traditional 45-degree pintle valve that is 60% open (prior art).

**[0034] FIG. 4A** is a perspective view of the Preferred Embodiment of the fluent control valve (FCV) according to the invention, showing a nozzle and a flow control surface (FCS) having only a very slight angle.

**[0035] FIG. 4B** is a side view of the fluent control valve (FCV) of **FIG. 4A**.

**[0036] FIG. 5A** is a CFD color graph of the temperature regions in the FCV according to the invention.

**[0037] FIG. 5B** is a CFD color graph of the pressure regions in the FCV according to the invention.

**[0038] FIG. 5C** is a CFD color graph of the Mach number distribution in the fluid flow in a FCV according to the present invention.

**[0039] FIG. 6** is a CFD color graph of the temperature regions and the HCS formed below the FCS in the PNI of the Preferred Embodiment of the FCV.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

**[0040]** The computational flow dynamic (CFD) illustrations submitted with this application are color graphs, whereby the various temperatures, pressures, and Mach conditions are indicated by colors and color gradations. In all illustrations, the highest

values are indicated by the color red and the lowest values by the color blue. A normal shock wave is generally indicated by the color yellow.

**[0041]** **FIGS. 1A and 1B** illustrate a traditional 45-degree valve **10** with a nozzle **11**, a 45-degree pintle **12**, a valve plenum **8**. The valve is traditionally set into a housing which locates the nozzle and pintle into position. The nozzle **11** has an upper surface **11A**, a nozzle inlet **4** and a nozzle exit **6**, and the pintle **12** has a tip **9A**. The portion of the pintle **12** that extends into the fluid flow provides a fluid control surface **9** that redirects the flow direction toward the nozzle exit **6**. A fluid dynamic throat **5A** forms between the nozzle inlet **4** and the pintle **12** as the valve **10** opens.

**[0042]** **FIG. 2A and FIG. 2B** illustrate the temperature and pressure regions, respectively, in the valve **10** when it is 90% open; **FIG. 2C** shows the regions of sonic, subsonic and supersonic fluid flow in the valve **10**. **FIGS. 3A - 3C** illustrate analogously the temperature, pressure, and Mach conditions of the valve **10** when the valve is 60% open. As seen in **FIGS. 2A and 2B**, the fluid in the plenum **8** is at high temperature and high pressure, both of which decrease gradually as the fluid flows toward the nozzle inlet **4** and impinges on the fluid control surface **9** of the 45-degree pintle **12**. The flow path toward the nozzle inlet **4** is bounded by the upper surface **11A** and the fluid control surface **9** and is contracting as it approaches the nozzle inlet **4**.

**[0043]** The ratio of the surface area of the fluid control surface **9** to the volume of the traditional pintle **12** is at its greatest at the tip **9A**. As shown in the **FIGS. 2A -3C**, an area of very high temperature and very high pressure forms at the tip **9A** downstream of a primary shock wave that forms in the fluid dynamic throat **5A**, even though the temperature and pressure of the fluid decrease as the fluid passes through the primary shock wave. This significantly increases the heat transfer into the pintle **12** via control surface **9**. Because of this, the tip **9A** is subject to extreme wear and material ablation during operation of the valve **10** and must be replaced frequently. Also, as the material is ablated, the geometry of the fluid control surface **9** changes, leading to significant

deterioration in valve performance, which results in decreased precision and fuel efficiency.

**[0044]** **FIGS. 4A** and **4B** illustrate the Preferred Embodiment of a fluent control valve (FCV) **100** according to the present invention. **FIGS. 5A - 6** are CFD color graphs that illustrate the temperature, pressure, and Mach conditions of flow during operation of the FCV **100**. As shown in **FIGS. 4A** and **4B**, the FCV **100** comprises a nozzle plate **103** and a fluid control plate **101** with a fluid control surface (FCS) **102**. The nozzle plate **103** has a flat nozzle-plate surface **103C**, a nozzle inlet **104** with a radiused nozzle inlet edge **103A**, a flared wall **103B**, and a nozzle exit **106**. A throat region **105** forms between the FCS **102** and the nozzle-plate surface **103C** as the FCV **100** opens. In the Preferred Embodiment shown, the nozzle plate **103** is fixed in position within a valve housing **114** and the fluid control plate **101** translates in a direction of operation indicated by arrow **116**.

**[0045]** Fluid flows into a valve plenum **108** from a supply line under high temperature and high pressure and, due to a pressure differential across the FCV **100**, flows across the nozzle-plate surface **103C** radially toward the nozzle inlet **104**. The velocity of the flow increases as a result of the area contraction ratio and then exceeds the velocity of sound as it flows through the smallest physical flow area of FCV **100** at the throat region **105**. Then, as the area expands at the nozzle inlet **104**, the flow becomes supersonic, turns 90 degrees in direction, and continues to increase in velocity toward the nozzle exit **106**.

**[0046]** With reference to **FIG. 4B**, the FCS **102** is formed with some small angle,  $\alpha$ . In the Preferred Embodiment,  $\alpha$  is 1 degree relative to a plane that is parallel to a valve plane **P** of the FCV **100**, indicated by dashed line **P**, so that a first distance **Z1** between the FCS **102** and the flat nozzle-plate surface **103C** is greater than a second distance **Z2** between the FCS **102** and the inner most edge of flat nozzle-plate surface **103C** where **103C** meets with nozzle inlet radius **103A**. The difference between **Z1** and **Z2**

may be on the order of a thousandth of an inch, depending upon design. The area contraction ratio of the fluid control plate **101** and the nozzle plate **103** is equal to:

$$CR = \frac{\int_0^{2\pi} dA_2}{\int_0^{2\pi} dA_1} = \frac{A_2}{A_1} = \frac{(2\pi R_2)Z_2}{(2\pi R_1)Z_1} = \frac{R_2 Z_2}{R_1 Z_1}$$

**[0047]** The FCV **100** requires less energy to open than the traditional pintle valve because, due to difference in distance between **Z1** and **Z2**, fluid remains present at line pressure for some small distance at the outer perimeter between the nozzle-plate surface **103C** and the FCS **102** when the FCV **100** is closed. Because of the pressure differential across the FCV **100**, the fluid provides immediate enhancement of the opening movement when the FCV **100** begins to open. As mentioned earlier, in the Preferred Embodiment, the fluid control plate **101** translates in the direction of operation **116** while the nozzle plate **103** remains stationary. It is within the scope of the invention, however, to construct a fluent control valve **100** according to the invention in which both the fluid control plate **101** and the nozzle plate **103** translate in the direction of operation **116**, in order to reduce time required to open the fluent control valve.

**[0048]** The very slight angle  $\alpha$  of the FCS **102** introduces virtually no obstruction into the flow stream and, since the fluid is equally balanced in all directions, fluid separation and/or turbulence is nearly nonexistent. Consequently, flow losses (pressure drop) across the FCV **100** are substantially smaller than those in traditional pintle valves. In addition, skin friction and heat transfer to surfaces on the fluid control plate **102** and the nozzle plate **103** are significantly reduced. Further, it has been found experimentally that the mass flow through the FCV **100** is linear with valve opening. This is another indication that recirculation and flow separation within the FCV **100** are nearly nonexistent.

**[0049]** In both the traditional pintle valve **10** and the FCV **100** according to the present invention, the fluid dynamic throat **5A** or the throat region **105**, respectively, leads into the corresponding nozzle inlet **4** or **104**. A comparison of **FIG. 5A** with **FIGS. 2A** and **3A** illustrates that the transition in the fluid flow from a very high temperature to a lower-temperature begins higher upstream in the throat region **105** in the FCV **100** than happens with the fluid dynamic throat **5A** of the traditional pintle valve **10**. The radiused edge **103A** of the nozzle **103** is the part of the nozzle that is most susceptible to material ablation resulting from rapid transfer of high heat. Thus, effectively moving the temperature transition region upstream of the radiused edge **103A** significantly reduces the amount of heat that is transferred to the radiused edge **103A** in the nozzle **103** of the FCV **100**, and thus, reduces the amount of material ablation. A similar shift in the transition area of a high pressure to lower pressure in the fluid flow can be seen when comparing **FIG. 5B** with **FIGS. 2B** and **3B**. The transition from a very high pressure to a lower pressure begins upstream from the radiused edge **103A** in the FCV **100**, whereas, in the traditional 45-degree pintle valve **10**, the transition occurs right at the radiused edge. The combined lower temperature and lower pressure at the radiused edge **103A** in the FCV **100** significantly reduces the amount of material ablation and, therefore, improves significantly the operational life and the performance of the FCV **100**.

**[0050]** **FIG. 6** illustrates the formation of a hydrodynamic “pintle” or hydrodynamic control surface (HCS) **115** that effectively turns the fluid 90 degrees toward the nozzle exit **106**. As the fluid flows through the throat region **105**, the fluid momentum is radially balanced and directed toward the center of the nozzle inlet **104**. In the nozzle inlet **104**, the fluid collides with fluid entering the inlet **104** from other sides and a fluid-fluid interaction occurs. As is illustrated by flow lines **117** the HCS **115** forms in the center of the nozzle inlet **104**, shown just above the FCS **102**. (Only one-half of the HCS **115** is shown in **FIG. 6**, extending from the center of the FCV **100** to the minus side on the X-axis. In reality, a mirror-reversed HCS **115** extends equally into the positive side.) Because the flow is redirected in a fluid-fluid interaction, rather than a fluid-solid



interaction that occurs when using a solid pintle, shear stresses on the fluid in the redirection process are minimal and, consequently, kinetic energy losses to friction and shearing are significantly reduced. In addition, the fluid-fluid interaction eliminates impingement of particles in the high velocity fluid on the solid surface of the nozzle **103** and FCS **102** of the Preferred Embodiment. This drastically reduces material erosion on both the fluid control plate **101** and nozzle **103** when compared to the pintle **12** of **Fig. 1** and nozzle **11**. The HCS **115** is an area of high temperature and high pressure that forms in the center of the nozzle inlet **104**, well away from the walls and the radiused edge of the nozzle **103** and directly beneath the FCS **102**. Because the FCS **102** of the FCV **100** is so flat and massive, it can well absorb the heat flux from the HCS **115** without the severe problems of material ablation that are so common with the traditional pintle valve **10**.

**[0051]** As also shown in **FIG. 6**, the throat region **105** between the fluid control plate **103** and the fluid control plate **101** forms earlier in the flow path, well above the radiused nozzle inlet edge **103A**. As a result, the temperature and pressure of the fluid is significantly lower at the radiused nozzle inlet edge **103A** than is the case with comparable flow in the traditional pintle valve **10**. For a comparison, see **FIG. 2A**. Again, lower temperature reduces the material stress at the nozzle inlet edge **103A**, thereby increasing the operating life of the nozzle **104**.

**[0052]** The Preferred Embodiment described herein is merely illustrative of the present invention. It should be understood that variations in construction of the present invention may be contemplated in view of the following claims, without straying from the intended scope and field of the invention herein disclosed.